Design of Large Working Area F-Theta Lens

by

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ABSTRACT

F-Theta lenses are different from normal camera lenses. It is one of the most important parts of laser scanning system. Besides, F-Theta lenses has been widely used in many other fields with high precision, such as biochip and missile tracking. In order to design an F-Theta lens used for laser marking machine, the desired amount of barrel distortion is introduced in an optical system so that the image height of the F-Theta lens is proportional to the scanning angle. In this paper, the design of the F-Thea lens with large working area is described in detail. Its working area is 640 mm in diameter.

Based on the theory of primary aberration, the first-order optical parameters are obtained at first by analyzing the features of the F-Theta lens. Then, the initial structure parameters are determined by PW method. Beginning with the initial structure, the final optimized F-Theta is achieved with Zemax optical design software. The designed F-Theta lens is compact with the simple structure and large working area. It consists of only four spherical lenses and its tube length is less than 100 mm. Its field of view is $\pm 28°$ which corresponds to $\pm 14°$ deflection angle of the oscillating mirrors. The focusing performances are within diffraction limit, the relative illumination is quit uniform across the working surface, and its distortion, calibrated F-Theta distortion, is less than 0.1%.

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1 INTRODUCTION

Laser technology and laser industry is the main symbol of the development of science and technology in the 20th century. In recent years, its development becomes more and more important and even a challenge for many traditional industrial fields that exist for decades. The advantage of using of lasers is directly related to three unique characteristics of laser light. The monochromaticity, the major appearance of laser light, makes it possible for extremely selective narrow-band excitation. The great spatial coherence of laser light allows people to obtain perfect focusing and directional irradiation even at high energy densities. The high directionality of laser light opens up the possibility of highly precision measurement. The combination of all these unique properties makes it more widely used in quite different applications, and gradually forms a modern optical manufacturing industry.

Laser marking technology is one of the biggest applications of laser technology. It is to use high-energy laser beam on the workpiece so that the material can be performed by material vaporization or color change of the chemical reaction, leaving a permanent marking. Laser marking can be used for a variety of text, symbols and patterns, and the character size can be from the order of millimeters to microns, which have special significance for the security of products. All-solid-state ultra-violet (UV) laser marking is a new technology developed in recent years, especially for metal marking, which permits sub-micron marking and has been widely used in microelectronics industry and biological engineering. Figure 1.1 is a sample image about laser marking.

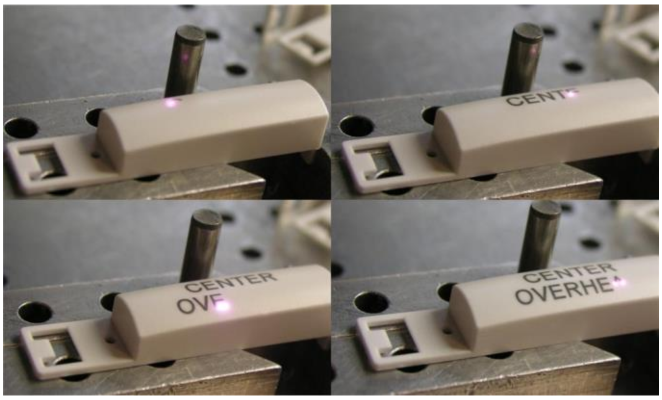

Figure 1.1 A sample image about laser marking (Source: Laser Impression Inc.)

Using lasers to do material processing takes advantage of nearly all of the features of laser light. First, the monochromaticity of laser light permits an easy way to control the depth of heat treatment of materials and allows for selective, non-thermal excitation that occurs either on the surface of the material or within the molecules of the surrounding medium, or both, by simply using different wavelengths of laser light. Compared to traditional mechanisms, some lasers, such as scanned cw lasers and pulsed lasers, provide with continuous operation and the shortest operating interval is about 10^{-15} s. Since the high directionality of laser light, a great spatial resolution that is better than 10 nm can be achieved by a strongly small range of heat- or photo- treatment of materials. Furthermore, laser light can be regards as a massless tool, there is no need to consider the mechanical stress between the workpiece and the laser light so that it does not affect the structure of the original workpiece and is more easy to deal with either brittle or soft materials. Besides, laser beams can be moved fast through scanning galvo mirror systems. Conventional heat source or mechanical gears can never compare with the moving speed of laser beams. Contrary to mechanical tool, laser light is not affected by wear and tear. This guarantees a sterile environment during the processing between the laser beam and the material, which is significant for medical and biological technology. Therefore, laser technology completely meets the needs of contemporary electric control techniques.

1.1 Main Genres of Marking Machines

A laser marking machine can be regarded as three main parts: a laser, a controller, and a workpiece. The laser is like a bullet – the high intensity beam emitted from it allows the controller to aimed at a surface and then to remove the material by the material vaporization or the chemical reaction. The controller is typically used by a computer through software to control the direction, intensity, speed of movement, and spread of the laser beam aimed at the surface. The workpiece is the target of the laser beam, but different workpieces need to be matched to different kinds of laser.

Laser marking control system is essential for laser marking machines. Therefore, the development of laser marking machines is the development process of marking control system. There are two main periods for laser marking machines: the X-Y table and the galvo-mirrors.

1. X-Y table

In the beginning, the so-called X-Y table is using the XY-Plotter control part to regulate the movement of laser beam. The figure 1.2 is a zoom view of an X-Y table.

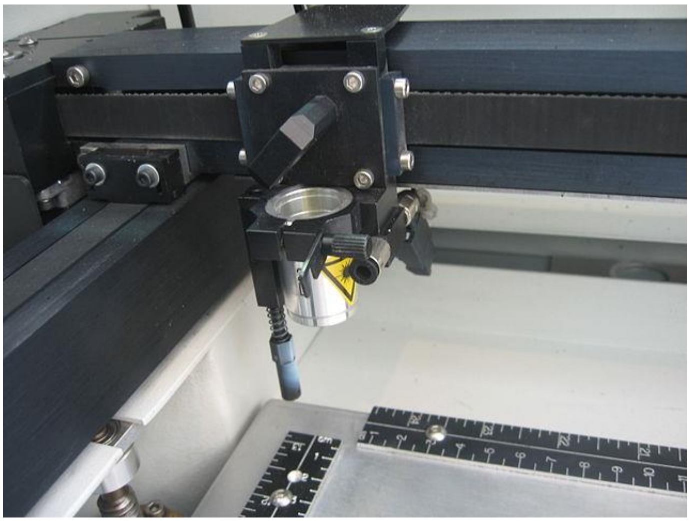

Figure 1.2 A zoom view of an X-Y table

The laser is often fixed to the sides of the table and guided by three mirrors angled at 45°. The mirrors direct the laser beam to move around in X and Y directions. As the figure 1.2 shown, a small focus lens is placed at the lower end of the original plotter pen to focus the light. And then the reproduced image is obtained directly under the print command of the drawing software by driving the operation of the optical path. The most obvious advantage of this approach is its large working area, which basically meets the lower precision marking requirements, and does not require special marking software. However, there are also many disadvantages such as slow marking speed, low control precision, large mechanical wear, poor reliability, and bulky volume. The large format laser marking system, like the X-Y table, has gradually withdrawn from the marking market, and now the large format marking machine is basically a high-speed large format system, which imitates this control system and is driven by servo moto. But as 3D dynamic focusing galvanometer scanning system gradually improved, the large format system is going to gradually disappear from the field of laser marking.

2. Galvo-Mirrors

Unlike the X-Y table, in this method both the workpiece and the laser are stationary and this typical control system uses a pair of galvo-mirrors to move the laser beam in the desired pattern, which allows the laser to work in raster (image is made up of individual dots) or vector (image is comprised of lines) modes. The Figure 1.3 is the working principle of the high-speed, computer-controlled galvanometer system. This

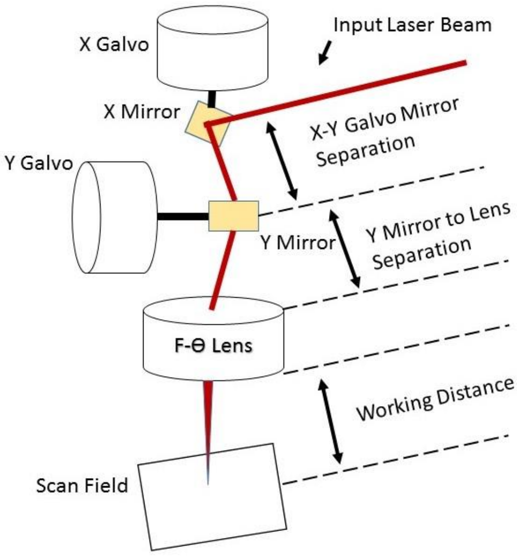

Figure 1.3 The working principle of the galvo-mirrors

control process in terms of speed and positioning accuracy are far more than the large format system. Besides, the use of position sensors and the design of the negative feedback loop further ensure the accuracy of the system, and the entire system scanning speed and repeat positioning precision has reached a new level so that laser marking control system with the galvo-mirrors to a large extent meets the industrial requirements of laser control.

In a laser scanning system, a laser beam is usually focused by an objective lens. According to the relative position of objective lens and galvanometer scanners, the developed scanners are divided into two types: pre-objective scanner and post-objective scanner. The advantage of the pre-objective configuration [Fig. 1.4 (a)] is that the laser

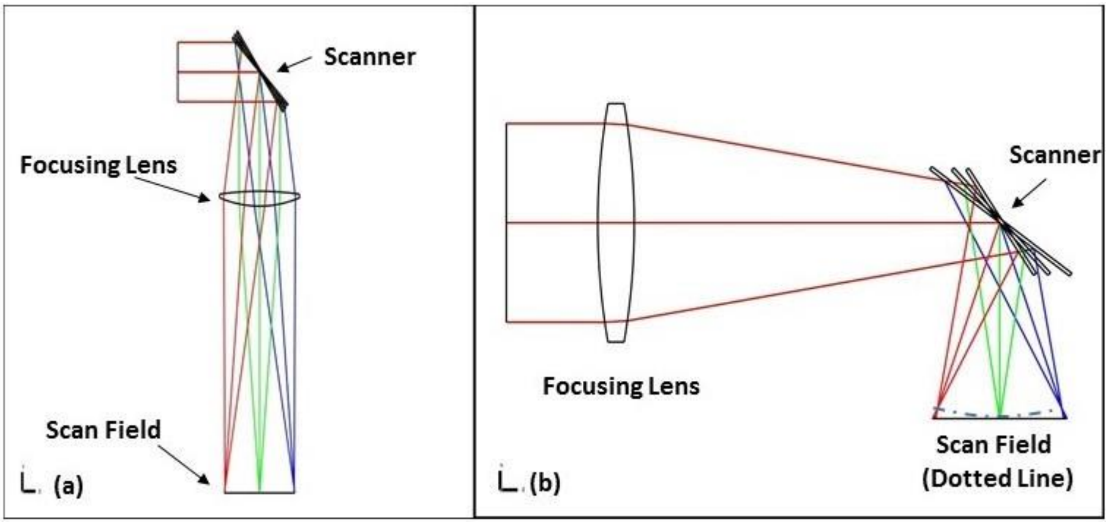

Figure 1.4. (a) Pre-objective scanning and (b) post-objective scanning

beam can be focused on a flat scan field. However, a higher design requirement is required due to the consideration of the both on-axis and off-axis images, and the difficulty of designing a large diameter focusing lens that is much larger than the laser beam. Correspondingly, the post-objective configuration [Fig. 1.4 (b)] only requires the consideration of the on-axis aberrations. The lens design is simple in construction and small in size, but the resultant scan field is not flat with the rotation of the scanning mirror.

Taking into account the structural characteristics of the laser marking machine and the working surface for the plane requirements, the most commonly used in practical applications is the pre-objective scanner, its working principle shown in Figure 1.3.

The system is mainly composed of a laser, a pair of galvo-mirrors, and an F-Theta lens. The laser beam is incident on the galvanometer by the beam expander, and the reflection angle of the galvanometer is controlled by the computer. The two mirrors can by scanned in the X and Y directions, respectively, to achieve the laser beam deflection, and then the laser beam is focused by the F-Theta lens to form a small spot on the workpiece to form a permanent mark. Different marking pattern is achieved through the preparation of the software program to control the scanning angle theta that guides the laser beam interacting with the whole surface.

The galvo-mirrors marking system that not only has wide range of applications, raster and vector modes, adjustable marking range, and a fast response speed, but also has high marking speed (hundreds of characters per second can be marked), strict accuracy, good optical path sealing performance, and strong adaptability to the environment, is considered to represent the future development of laser marking machine with broad application prospects.

1.2 The Basic Principle of F-Theta Lenses

F-theta lens is generally composed of two or more spherical lenses or aspherical lenses, which has a special aberration characteristics. For an ordinary distortion-free lens, the incident light beam through the lens produces an image height that follows the rule:

$$h = f \cdot tan\theta \tag{1.1}$$

, where $h =$ image height

$f =$ lens focal length

$\theta = \text{angle of incident}$

Thus, if this kind of lens is used in laser scanning system, the image height and the angle of incident will be the nonlinear relationship. That means when the angle of incident changes linearly by a mirror rotation with a constant angular velocity, the scanning speed is no longer constant; the exposure time will vary with the different velocity. In order to achieve a same scanning velocity across the workpiece, a certain amount of distortion is introduced so that the image height follows the relationship:

$$h = f \cdot \theta \tag{1.2}$$

At this time the introduced distortion is Δh, it can be expressed as

$$\Delta h = f \cdot \theta - f \cdot tan\theta = f(\theta - tan\theta) \tag{1.3}$$

F-theta lenses are designed to produce the distortion Δh so that the image position and the incident of angle satisfies the linear relationship. Therefore, lenses designed in this way are called F-theta lenses.

The working area is determined by the incident of angle and the effective focal length. The incident of angle is usually $\pm 20°$ or $\pm 25°$. When the same laser marking machine is used for the different size of the workpiece, it often needs to replace the lens with different working area. Once the linear relationship is satisfied, the focal length of the f-theta lens can be determined by the image height and the incident of angle.

2 F-THETA LENS DESIGN THEORY

2.1 The Principle of F-Theta Lenses

As shown in Figure 2.1 for the ideal optical system schematic diagram, O_1 and O_k are the first and last faces of the ideal optical system, respectively. FO_1O_kF' is the optical axis. The incoming ray with the height h is focused by the optical system intersecting at the rear focal point F'. If the incoming ray parallel to the optical axis is incident from the image side, it will intersect with the optical axis at the object focal point F. The incident height h, the angle u between the optical axis and the emergent light from the image side, and the front focal length f satisfy the relationship shown in the expression below:

$$h = f \times \tan(u) \tag{2.1}$$

This relationship reflects the characteristics of the principal point and the focal point in the ideal optical system. According to this characteristic, if u and f are known, the ideal image height can be obtained.

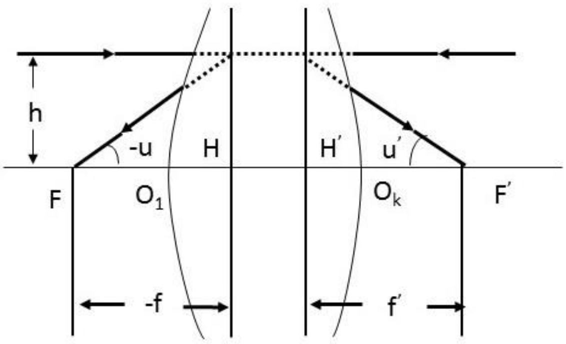

Figure 2.1. The ideal optical system schematic diagram

The imaging properties of the general system shown in Figure 2.2 also reflects the object-image relationships of a telescopes objective. For an ideal optical system, the object height y is proportional to the tangent of the image ray angle θ', which is

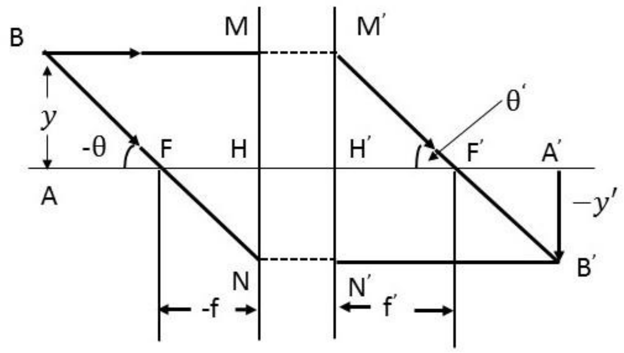

Figure 2.2. The object-image relationships

$$y = f' \times tan\theta' \tag{2.2}$$

The image height –y’ is proportional to the tangent of the object ray angle θ (the field angle), which is

$$-y' = f \times tan\theta \tag{2.3}$$

Unlike the telescope objective, the incident light beam through the lens produces an image height –y’ that is directly proportional to the field angle θ. As shown in Figure 2.3., the field angle, the focal length of the F-Theta lens, and the image height satisfy the relationship:

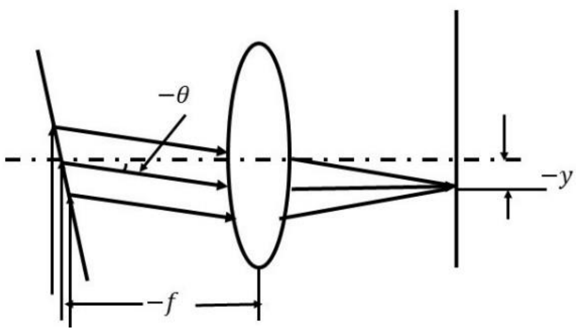

Figure 2.3. Principle of F-Theta lens

$$-y' = f \times \theta \tag{2.4}$$

It means when the focal length of the F-Theta lens is constant, the image height and the field angle satisfy a linear relationship.

2.2 Idea of the Optical Design

In laser marking system, F-Theta lens works with single wavelength. According to the different workpieces that are going to interact with high-energy laser, the common operating wavelengths are 0.6328μm, 1.064μm, and 10.6μm laser wavelengths. Laser marking machine's working surface, F-Theta lens image plane, is usually a plane. The equivalent stop of the F-Theta lens is at the X oscillating scanning mirror where the input laser beam first arrived as shown in Figure 1.3, and its diameter equals to the input laser beam. From the relative position of the F-Theta lens and the galvanometer scanner, it belongs to the pre-objective scanning, which has small relative aperture of F-Theta lens and large field of view. Therefore, the main concern of this kind of optical system is correcting the aberrations associated with the field of view.

2.3 The Linear Relationship of F-Theta Lens

Since the F-Theta lens image height and the field angle satisfy the linear relationship shown in formula (2-4), the linear control of the marking speed can be achieved by controlling the incident angle through the F-Theta lens surface. As long as X and Y galvo-mirrors rotate with a constant angular velocity, the laser beam will be focused across the workpiece with a constant scanning speed as well.

As illustrated in Figure 2.4., the curves of two functions are $y = \theta$ and $y = \tan\theta$.

The image height y of the ideal imaging lens is proportional to the tangent of the field of view, $\tan\theta$, and the image height y of the F-Theta lens is proportional to the field of

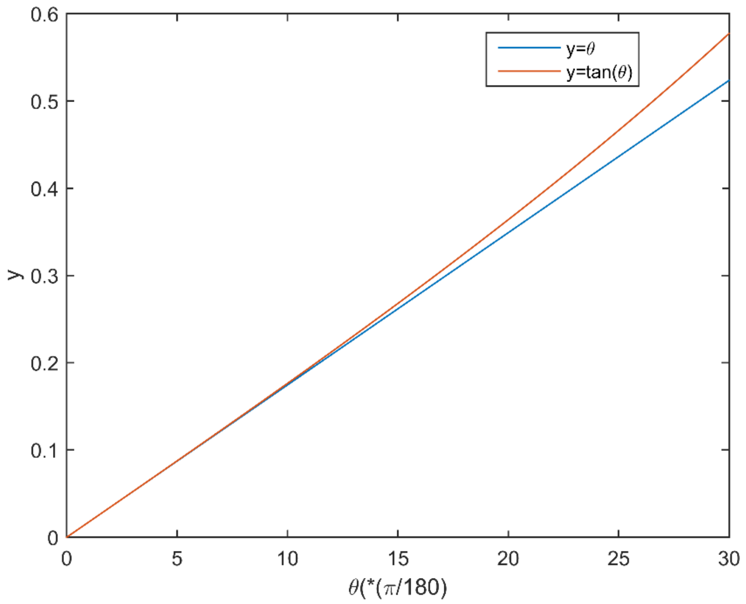

Figure 2.4 The curves of $\mathbf{y = \theta}$ and $\mathbf{y = \tan\theta}$

view θ. When the field of view θ is small, the two curves almost overlap each other, which means the image height y of the F-Theta lens and the ideal image height y are close to each other. But as the angle θ increases, the deviation of the two curves becomes more obvious. Due to the fact the real ray bends more than the paraxial ray, distortion is a change in magnification as a function of the field of view. Negative distortion called barrel distortion occurs when the real ray bends less than the real paraxial ray with increasing the image height y. Conversely, positive distortion called pincushion distortion results when the real ray bends more than the real paraxial ray. In the F-Theta lens system, the actual image height satisfies the relation of $f \times \theta$, which is smaller than the ideal image height $f \times tan\theta$. Therefore, the essence of F-Theta lens design is to introduce barrel distortion, so that with increasing the field of view it makes actual image height Y deviate from the function $y = \tan\theta$ but close to the function

$y = \theta$ as possible.

Because the optical system cannot completely correct all the aberrations, F-Theta lens cannot fully meet the linear relationship. The deviation of the actual image height Y from the $f \times \theta$ linear relationship is defined as the relative deviation $q_{f\theta}$. And as long as the relative deviation $q_{f\theta}$ is smaller than 0.5%, the lens system can be considered to meet the F-Theta linear relationship that can be used for the marking machine in practical use. The condition about the relative deviation to the F-Theta linear relation is given by

$$\mathrm{q}_{f\theta} = \frac{Y - f \times \theta}{f \times \theta} < 0.5\% \qquad (2.5)$$

, where $Y =$ real image height

$f =$ lens focal length

$\theta =$ field of view

Because of the mechanical structure of galvanometer laser marking machine, the stop should be put outside the optical system to introduce distortion. At the same time, due to the need to introduce barrel distortion, the lenses near the stop should be bend to it.

2.4 The Flat Field Condition

F-Theta lens is an optical system which has large field of view and small relative apertures. For a large field of view optical system, in addition to correcting the aberration for the on-axis point, the off-axis point aberration must also be corrected. One of the major aberrations that impede the performance of large field of view is field curvature, so the correction of field curvature is important for F-Theta lenses.

Laser marking machine is generally used to make characters or patterns in the plane. Since the working surface of F-Theta lens is usually flat, the F-Theta lens design must meet the flat field condition which is shown in the follow equation.

$$\sum_k \frac{\phi_k}{n_k} \tag{2.6}$$

, where ϕ_k and n_k are the focal power and the refractive index of the k-th lens in the F-Theta lens, respectively. It is shown that the F-Theta lens should contain both positive and negative optical powers, and the positive and negative lenses are made of different glass materials.

2.5 Analysis of Other Aberrations

Since F-Theta lens relative belongs to such an optical system with small relative aperture, its spherical aberration and coma are not primary factors to influence on the focusing performance. Moreover, the input beam for the F-Theta lens in marking machine is usually single wavelength laser, in which case there is no need to correct the chromatic aberration. Therefore, after introducing the barrel distortion and correcting the field curvature, the monochromatic aberration that should be considered is astigmatism only.

Astigmatism is caused by different power in the tangential direction and sagittal direction so that the rays that propagates in those two directions will be sharp focus at two different locations. After the refraction of the wavefront by the optical system, the rays lose their symmetry and are no longer spherical waves, converging on two mutually perpendicular short lines. Sagittal focus is where the sagittal rays focus, and a line image in the meridional plane is formed. Tangential focus is where the tangential rays focus, and a line image is formed perpendicular to the meridional plane. The distance between the two focal lines is caller astigmatism.

To correct the astigmatism of the optical system, there are special requirements on the structure of the optical system. It is expected that two adjacent optical surfaces that belong to two adjoining lenses bend against each other to satisfy a kind of symmetry structure so that the astigmatism produced by the front group lenses can be compensated by the last group lenses. As shown in Figure 2.5., H_1' and H_2 refer to the rear principle

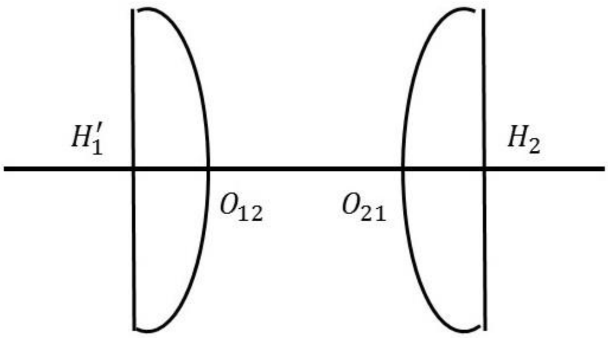

Figure 2.5 Correction of astigmatism in the lens structure

plane of the front group and the front principle plane of the rear group, respectively. O_{12} and O_{21} are the intersections of the two adjacent optical surfaces and the optical axis.

In order to obtain a good marking effect, the focusing performance is required to be within diffraction limited. This requires that when the optical system is no vignetting and the relative illumination is distributed uniformly, all the laser beam through the optical system should be well focused with the airy spot.

In accordance with the actual conditions of use, the optical system can be divided into small field of view with large aperture system, large field of view with small aperture system, and large field of view with large aperture system. Different types of systems require different aberration corrections. The optical system with small field of view and large aperture mainly considers the spherical aberration and the lateral chromatic aberration, which belongs to the small aberration system. The image quality can be evaluated by the Rayleigh criterion based on the wave aberration. Apart from spherical aberration, lateral chromatic aberration, and other on-axis aberrations, the system with large field of view and large aperture, also known as large aberration system, also needs to consider coma, astigmatism, field curvature, distortion, axial chromatic aberration, and other off-axis aberration.

The F-Theta lens designed in this paper belongs to the optical system that has a large field of view and a small relative aperture. Due to its small relative aperture, spherical aberration and lateral chromatic aberration are easier to correct. At the same time because of its large field of view, the off-axis aberrations, especially astigmatism and field curvature, should be corrected strictly. Unlike an ordinary photographic objective, when the F-Theta lens is used in a laser marking machine, it operates at a single laser wavelength emitted by the laser, without the need to correct chromatic aberration. Moreover, since the small diameter of the incident laser beam, the influence of the coma aberration is trivial and can be corrected by changing the shape factor of the lens. According to Section 2.3, the essence of F-Theta lens design is to introduce barrel distortion. Distortion, field curvature and astigmatism are three monochromatic aberrations that need to be rigorously corrected when designing the F-Theta lens used in marking machine. From the structure of the optical system, the correction of the three aberrations should meet the following requirements:

1. Introduce of barrel distortion

Due to the mechanical structure of the laser marking machine itself, the F-Theta lens can be convenient to introduce barrel distortion. Thus, the stop should be put outside the optical system and the lenses near the stop should be bend to it at the same time.

2. Correction of field curvature

The correction of the field curvature can be performed according to equation (2.6). The F-Theta lens should contain both positive and negative optical powers, and the positive and negative lenses are made of different glass materials.

3. Balance of astigmatism

Depending on the concept of astigmatism and the cause of it, the lens structure shown in Fig. 2.5 can be selected, where the two lenses placed symmetrically in the optical system can be used to balance astigmatism.

3 DETERMINATION OF INITIAL STRUCTURE

There are many ways to determine the initial structure of an optical system, which can be divided into two categories. One is looking up the literature and patent library, the other is using P-W method. In this paper, the initial structure of the F-Theta lens is in accordance with the primary aberration theory, using P-W method to obtain the solution. The initial structure obtained by this method is an approximation, and the high-order aberration is not taken into account in the solving process, and the lens thickness is omitted. In order to meet the practical requirements the optimized F-Theta lens will be described in the next chapter.

3.1 Design Structure of the F-Theta Lens

As a result of the marking system structure restrictions, scanning galvanometer deflection angle cannot be too large, generally no more than $\pm 15^{\circ}$, that is, the incident angle of the laser beam does not exceed $\pm 30^{\circ}$. When a large area $450 \times 150\ \mathrm{mm}^2$ of the computer keyboard needs to be marked, due to the small work area completing the entire computer keyboard marking often requires several translations of high-precision translation platform with the existing laser marking machine. In order to eliminate the marking errors caused by the platform shift, reducing equipment costs, and marking a clear pattern, the F-Theta lens is expected with a working area about $\Phi 634\ \mathrm{mm}$. After determining the F-Theta lens working area and field of view, the focal length is approximately 600 mm according to equation (2.4). The aperture stop is located at X oscillate mirror where the laser beam first arrives and has a diameter equal to the diameter of the incident laser beam, approximately 10 mm. According to the actual marking machine structure, the distance between the aperture stop and the F-Theta lens distance is 32 mm. The F number of F-Theta lens is close to F/65. For a Nd:YAG lasers with a wavelength of 1.064 μm, the radius of Airy disc can be calculated as follow

$$\mathbf{a} = 1.22\lambda \times \boldsymbol{F}/\# \tag{3.1}$$

Thus the half width of the Airy disc is about 85 μm. In order to achieve the highest marking resolution, the spot diagram should be controlled within the Airy disc.

3.2 Distribution of Focal Power

According to the flat field condition equation (2.6), the F-Theta lens should contain both positive and negative optical powers, and the positive and negative lenses are made of different glass materials. For the sake of simplicity, the initial structure is calculated assuming that the system has two thin lenses, positive and negative. The whole system has seven first-order optical parameters, such as four radius of curvature, one interval and the refractive index of two lens glass. For the chromatic aberration problem, since the optical system is operated under monochromatic light, there is no need to correct the chromatic aberration. To satisfy the flat field condition, two different optical glasses K9 and ZF6 are selected. In order to meet the compact structure requirements, the interval between the two lenses is initially set at 100 mm. With considering the total power and the flat field requirement, there are only two free parameters available for correcting the aberration, and it is difficult to simultaneously correct all the aberrations. Therefore, in the process of optimizing the design, more optimization parameters can be introduced by complicating the initial structure.

Assuming that the initial structure of the optical system is composed of only two spherical lenses, the focal power can be distributed by the following equation

$$\begin{cases} \dfrac{\phi}{n_1} + \dfrac{\phi_2}{n_2} = 0 \\ \phi_1 + \phi_2 - d\phi_1\phi_2 = 1 \end{cases} \tag{3.2}$$

, which is deduced by the flat filed condition equation (2.6) and the requirement of the normalized focal power. Using the normalized interval d=1/6, and the refractive index $n_1 = 1.50619$ and $n_2 = 1.72754$ of the two lenses, two solutions A and B about the normalized focal powers are obtained by the equation above.

$$\text{A:}\begin{cases} \phi_1 = -1.93487 \\ \phi_2 = 2.219922 \end{cases} \qquad \text{B:}\begin{cases} \phi_1 = 2.70365 \\ \phi_2 = -3.10098 \end{cases} \tag{3.3}$$

3.3 Initial Structure Calculation

According to the primary aberration theory and P, W method, the primary aberration coefficients formula for the thin lens system expressed by P and W is as follows:

$$\begin{cases} \sum S_1 = \sum hP \\ \sum S_2 = \sum h_p P + j \sum W \\ \sum S_3 = \sum \dfrac{h_p^2}{h} P + 2j \sum \dfrac{h_p}{h} W + j^2 \sum \phi \\ \sum S_5 = \sum \dfrac{h_p^3}{h^2} P + 3j \sum \dfrac{h_p^2}{h^2} W + j^2 \sum \dfrac{h_p}{h} \phi(3+\mu) \end{cases} \tag{3.4}$$

$$\mu = \frac{\sum \frac{\varphi}{n}}{\phi} \tag{3.5}$$

, where S_1, S_2, S_3, and S_5 are the primary spherical aberration, coma, astigmatism and distortion coefficients; h is the incident height of the marginal ray on the thin lens surface, and h_p is the incident height of the primary ray on the lens; φ is the optical power of the thin lens surface, ϕ is the optical power of the thin lens; j is the Smith-Helmholtz invariant, which is one unit under the normalized condition. P and W are the aberration parameters of a single lens in a thin lens group, and are simply expressed as the function forms as follows:

$$\begin{cases} P_1 = P_1(n_1, \phi_1, Q_1) \\ W_1 = W_1(n_1, \phi_1, Q_1) \\ P_2 = P_2(n_2, \phi_2, Q_2) \\ W_2 = W_2(n_2, \phi_2, Q_2) \end{cases} \tag{3.6}$$

, where 1 and 2 indicate the parameters of the first and second lenses, Q_1 and Q_2 are the shape factors of the two lenses respectively. The aberration parameters P and W of the single lens and the basic aberration parameter $\overline{\mathrm{P}^{\infty}}$ and $\overline{\mathrm{W}^{\infty}}$ satisfy the following relationship:

$$\begin{cases} \overline{\mathrm{P}^{\infty}} = \left(\frac{\Delta u}{\Delta \frac{1}{n}}\right)^2 \Delta \frac{u}{n} \\ \overline{\mathrm{W}^{\infty}} = -\frac{\Delta u}{\Delta \frac{1}{n}} \Delta \frac{u}{n} \end{cases} \tag{3.7}$$

$$\bar{\mathrm{u}} = \frac{u}{h\phi} \tag{3.8}$$

, where Δ represents the difference between the image side and the object side of the corresponding optical surface. The paraxial raytracing is performed under the normalized condition of the following equation (3-9),

$$\begin{cases} u_1 = 0 \\ u_{p1} = -1 \\ \phi = 1 \\ h_1 = 1 \\ u_2' = 1 \\ j = -nh_1u_{p1} = 1 \\ l_p = \dfrac{32}{600} \\ d = \dfrac{100}{600} \end{cases} \tag{3.9}$$

The first-order optical parameters are obtained:

$$\begin{cases} u_1 = 0, h_1 = 1 \\ u_2 = u_1' = u_1 + h_1\phi_1 = \phi_1 \\ h_2 = h_1 - du_1' = 1 - d\phi_1 \\ h_{p1} = -l_pu_{p1} = l_p \\ u_2' = 1, u_{p1} = -1 \\ u_{p2} = u_{p1}' = u_{p1} + h_{p1}\phi_1 = -1 + l_p\phi_1 \\ h_{p2} = h_{p1} - du_{p1}' = l_p + d - dl_p\phi_1 \end{cases} \tag{3.10}$$

Substituting the first-order parameters obtained in (3-10) into (3-7) yields the basic aberration parameters.

$$\begin{cases} \overline{P^\infty} = \left(1 + \dfrac{2}{n}\right)Q^2 + \dfrac{3}{n-1}Q + \dfrac{n}{(n-1)^2} \\ \overline{W^\infty} = \left(1 + \dfrac{1}{n}\right)Q + \dfrac{1}{n-1} \end{cases} \tag{3.11}$$

Further, the obtained normalized first-order quantities and the basic aberration parameters obtained by the above equation (3-11) are successively substituted into the equations (3-6) and (3-5). The expression of the primary aberration coefficients related to the two thin lens shape factors can be obtained from equation (3-4):

$$\begin{cases} \sum S_1 = S_1(\phi_1, \phi_2, Q_1, Q_2) \\ \sum S_2 = S_2(\phi_1, \phi_2, Q_1, Q_2) \\ \sum S_3 = S_3(\phi_1, \phi_2, Q_1, Q_2) \\ \sum S_5 = S_5(\phi_1, \phi_2, Q_1, Q_2) \end{cases} \tag{3.12}$$

The above equation shows that the primary aberration coefficients such as spherical aberration, coma, astigmatism, and distortion are only related to the shape factors Q_1 and Q_2 of the thin lens as long as the power is selected, and different Q values can be solved by any two of the equations.

From the relationship among the shape factor, the lens surface curvature and the optical power

$$\begin{cases} (n-1)(c_2-c_1)=\phi \\ c_2-Q=\phi \end{cases} \tag{3.13}$$

, the curvature of the lens surface can be obtained as:

$$\begin{cases} c_1=\dfrac{1+Q}{\phi}-\dfrac{\phi}{n-1} \\ c_2=\dfrac{1+Q}{\phi} \end{cases} \tag{3.14}$$

From the above equation, the four radii of curvature of the F-Theta lens in the initial structure can be calculated. The real solutions are listed in Tables 1 and 2 below.

Tab. 1 Solutions of initial structure when the focal power equals to group A

Initial solutions	Q_1	Q_2	r_{11}	r_{12}	r_{21}	r_{22}
1	-7.06855	-4.64342	86.2217	191.301	-127.876	-365.463
2	-2.7043	-1.71401	127.572	681.171	-177.935	-1864.87
3	-6.65886	-4.43913	88.9276	205.151	-130.435	-387.171
4	-2.81199	-2.26287	126.08	640.69	-165.776	-1054.37
5	-5.98268	-4.3203	93.7852	232.991	-131.971	-401.028
6	-1.85658	-2.53948	140.677	1355.3	-160.257	-864.923

Tab. 2 Solutions of initial structure when the focal power equals to group B

Initial solutions	Q_1	Q_2	r_{11}	r_{12}	r_{21}	r_{22}
1	-1.190080	-0.678907	-110.8760	-8534.480	144.275	-5794.560
2	0.018575	1.169820	-120.8560	1593.420	168.419	-857.487
3	-2.521600	1.073760	-101.6270	-1066.110	166.967	-897.207
4	0.397255	2.069550	-124.3690	1160.980	183.352	-606.145
5	-6.996980	0.448593	-79.3730	-270.502	158.098	-1284.410
6	-5.937570	-2.592130	-83.7123	-328.541	125.636	1168.620

7	-1.195350	-3.674760	-110.8360	-8303.930	117.078	695.610
8	0.866743	2.243860	-129.0130	868.996	186.556	-573.573

When the focal power is chosen as solution A shown in the equation (3.3), the first two solutions above Tab. 1 can be obtained by solving the equation $\begin{cases}\sum S_1 = 0\\ \sum S_2 = 0\end{cases}$. With the same method, by solving the equations $\begin{cases}\sum S_1 = 0\\ \sum S_3 = 0\end{cases}$ and $\begin{cases}\sum S_2 = 0\\ \sum S_3 = 0\end{cases}$ the rest four solutions as listed in Tab.1 are obtained. In Tab.1 the first radius of each solutions is positive, which means the first surface of each initial structure that near the stop is bending against the stop. Therefore, it contradicts above design idea. When the focal power is chosen as solution B, eight solutions are obtained as listed in Tab.2 with the same reason. By the optical design software ZEMAX, the corresponding primary spherical aberration, coma, astigmatism, distortion, and field curvature coefficients can be obtained and listed in Table 3 as follow.

Tab. 3 The Seidal aberration coefficients of the initial structures in Tab. 2

Solutions in Tab. 2	SPHE	COMA	ASTI	DISC	FCUR
1	0.000058	0.000007	0.000001	0.000000	0.000000
2	0.000295	0.000021	0.000001	0.000000	0.000000
3	0.000287	0.000022	0.000001	0.000000	0.000000
4	0.000260	0.000018	0.000001	0.000000	0.000000
5	0.000264	0.000026	0.000001	0.000000	0.000000
6	0.000460	0.000037	0.000002	0.000000	0.000000
7	0.000584	0.000034	0.000002	0.000000	0.000000
8	0.000254	0.000018	0.000001	0.000000	0.000000

By comparison, the aberration coefficients value of the first group is the smallest, and is selected as the initial structure for further optimization design.

In order to calculate the initial structure, the thickness of the lens is omitted at first. But it is an approximate solution and must be optimized to obtain an optical system that meets the practical requirements. Thus, by using ZEMAX the thin lenses of the initial structure is thicken to optimize the optical system as shown is Figure 3.1. The field angle is 20 °, and the image height is about 228mm that is less than the required working area. Moreover, the two lenses are too thick so that the requirement of their material and processing cannot be tolerant.

The optical system diagram of the initial structure is shown in Figure 3.1, which is calculated when two primary aberrations are corrected simultaneously. To correct for

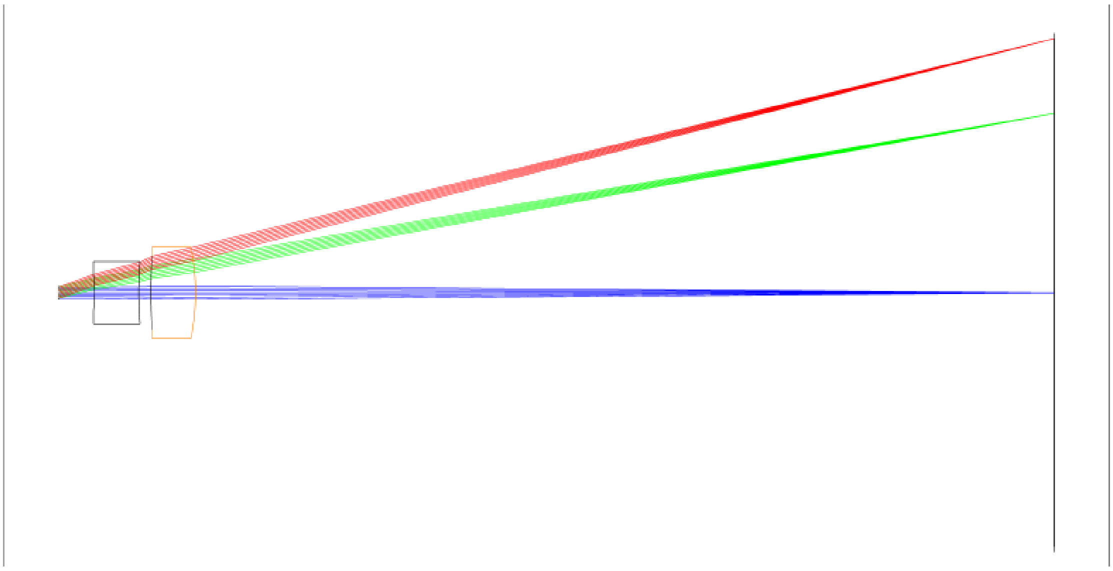

Fig. 3.1 The structure for the first time optimization

more aberrations at the same time for achieving a larger working area, the variable parameters of the optical system must be increased by appropriately complicating the system through Zemax and establishing a series of rational merit functions under reasonable constraint conditions.

4 F-THETA LENS DESIGN

4.1 Introduction

Currently, most commonly used lasers are high power Nd:YAG lasers (λ ≈ 1.064 μm) and CO2 lasers (λ ≈ 1.064 μm). The interaction processes between laser light and matter depend on the material characteristic and the property of the laser beam. Since Nd:YAG lasers produce shorter laser wavelengths it has a small focal spot and is well absorbed by metals so that they are suitable for high-resolution marking on metals. However, CO2 lasers operate in the infrared, wood products, glass, polymers and most of the transparent material has a good effect of absorbing, and thus it is proper for marking on non-metallic surfaces.

The disadvantage of using Nd:YAG lasers and CO2 lasers is directly related to their thermal effects, such as thermal damage produced by high-irradiance continuous CO2 lasers and higher thermal diffusivity, which has the serious impact of the marking precision. In contrast, when the ultraviolet light produced by the excimer laser is used as a substitute, the laser beam causes significant material vaporization due to the photochemical effects occurring on the surface of the material. The material is not heated, only the surface of the material is vaporized, leaving a mark on the workpiece. Therefore, the sharp edge of the marking pattern can be obtained by using the excimer laser. Because of the absorption of ultraviolet light, the interaction between the laser light and the material occurs only on the surface of the material. There is almost no thermal damage, so the excimer laser is more appropriate for marking materials. An excimer laser is a high-power and high repetition rate laser which is commonly used in the production of 193nm, 248nm, 305nm, and 351nm wavelengths of the laser light. It has been widely used in many aspects of scientific research. In recent years, excimer laser in operation reliability, power and average energy level, working gas life, maintenance-free cycle and many other properties have made great progress, which basically reached the level of industrial applications. It has become the most promising new type of industrial lasers after Nd:YAG lasers and CO2 lasers.

4.2 Image Quality Evaluation

An image is a complex physical matter with a lot of detail and characteristics. In optimizing the design to correct aberrations, it is not necessary and impossible to correct all aberrations to zero at the same time. Because the measure of image quality depends on the application and on the features that are considered. As with F-Theta lenses, in order to achieving a constant scanning speed barrel the barrel distortion are introduced to satisfy the linear relationship between the field of view and the focal length of the F-Theta lens. Additional, since lenses cannot be perfectly manufactured some aberrations are bound to exist. Thus, some aberrations only need to be corrected to a certain degree. As we can see from Section 2.3, different optical systems require different aberrations, and the evaluation method is different. There are many methods of image quality evaluation, among which Rayleigh criterion, Strehl ratio, encircled energy, spot diagrams and MTF are commonly used.

Due to the designed F-Theta lens is an optical system with a larger field of view and a small aperture, using the Strehl ratio as its image quality evaluation method is appropriate. According to the special application of F-Theta lenses, the comprehensive measure of the image quality must also be combined with other image quality metrics, such as spot diagrams, distortion and field curvature plot, relative illumination, and encircled energy. Therefore, the image quality metrics mentioned above are introduced here.

When there are aberrations present in the image, two effects may occur. The shape of the diffraction pattern may become skewed, which depends on the aberration. The other one is that there is less energy in the central ring and more in the outer rings. In 1894 Strehl proposed an indicator, Strehl Ratio, to determine the image quality of an optical system. The Strehl ratio corresponds to the ratio of the peak of the diffraction pattern to that of a diffraction-limited or perfect system. Strehl pointed out that when the Strehl ration is equal to 0.5 or greater, the optical system can be considered perfect and its produced image are often considered functionally equivalent to diffraction-limited image. The Strehl ratio as a description of system quality is a relatively rigorous and reliable image quality evaluation method, which only makes sense in systems with quite low wave aberrations.

If a lot of rays from one single object point filled with the pupil area are traced through an optical system, due to the presence of aberrations the image after focusing is no longer a single point. Spot diagram is an impression of the geometrical extension of the image point in the geometrical approximation. It shows the distribution of the rays on the image plane, reflecting the characteristics of a lot of aberrations of the whole system. Generally, spot diagram is suitable for large aberration system. However, it is not easy to distinguish typical aberrations from the diagram and does not give a correct figure of merit for diffraction-limited systems.

Distortion and field curvature curves are aberration curves that can directly reflect the distortion, field curvature, and astigmatism of the optical system. The distortion does not affect the clarity of the image, but will change the shape of the image. For F-Theta lenses, because of its essence is to introduce barrel distortion, and the relative deviation $q_{f\theta}$ must meet the equation (2.5) after introducing of the barrel distortion. Therefore, the distortion curve is an important indicator to evaluate the F-Theta lens. In addition, the F-Theta lens designed in this paper is for laser marking machine, the field curvature must be corrected for the flat working surface so that the field curvature is another important indicator to evaluate the F-Theta lens.

Relative illuminance is the ratio of the off-axis illumination to the on-axis illumination on the image plane. It is related to the field of view and decreases with the increase of the field of view. For an ideal optical system, the relative illumination and the field of view follow the $\cos^4\theta$ law as shown below

$$E = E_0 \cdot cos^4\theta \tag{4.1}$$

, where E =On-axis illumination

E_0 =Off-axis illumination

θ =Field of view

It means that the edge illumination is reduced by a factor of $\cos^4\theta$ with the field of view θ. This relationship is not true for all systems, such as for some wide-angle objective, the vignetting is sometimes used to improve the image edge illumination. At this time, the illumination reduction factor is $\cos^3\theta$. It can be seen that, regardless of the vignetting of the optical system, when the field of view increases, the impact of reduced edge illumination is quite serious. Thus, the larger field of view of the optical system, the more difficult to control the off-axis illumination. Since one of the requirements for laser marking is evenly distribution of the center and edge illumination, a symmetric engraved line can be obtained. Therefore, the relative illumination is another necessary indicator to evaluate the quality of the F-Theta lens.

Encircled energy is an important quality criterion for the F-Theta lens, which measures the energy of the intensity of a spot as the transmitted power through a stop with variable radius. After the laser beam pass through the F-Theta lens, the marking effect is better with the more concentrated energy.

4.3 Design Results and Evaluation

As shown is Fig. 4.1, the optimized F-Theta lens is composed of four spherical lenses. The first two lenses made of K9 (Nd: 1.5164, Vd: 64.133) while the other two lenses are ZF6 (Nd: 1.7522, Vd: 27.543). The largest aperture among them is approximately 120 mm. The aperture stop whose diameter is 10 mm is left to the front surface of the first lens, which is out of the lens system. And the distance between the stop and the surface is 32 mm, considering the structure of practical laser marking machine. Its working area is 640 mm in diameter. And the effective focal length, field of view, and F/# are 650 mm, $56°$ and F/65, respectively. The distance from the back surface of the last lens to the image plane is 830mm. The optical system is compact. The distance from the front surface of the first lens to the back surface of the last lens is only 95 mm.

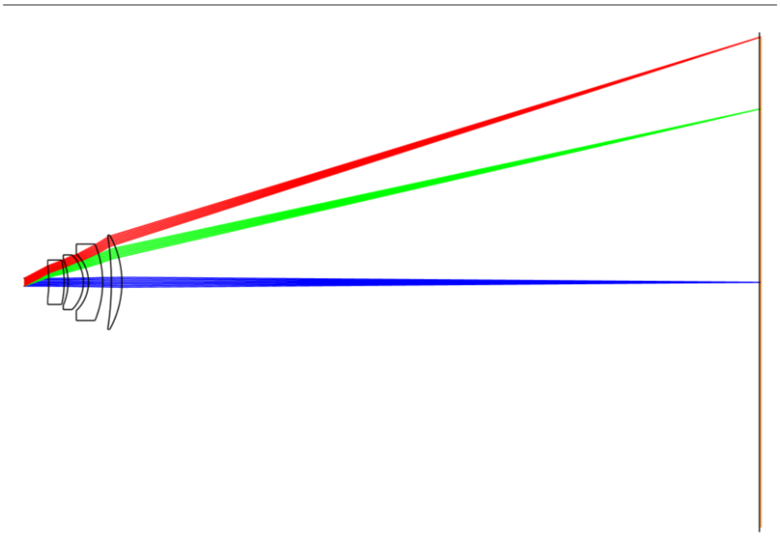

Fig. 4.1 The structure for the optimized F-Theta lens

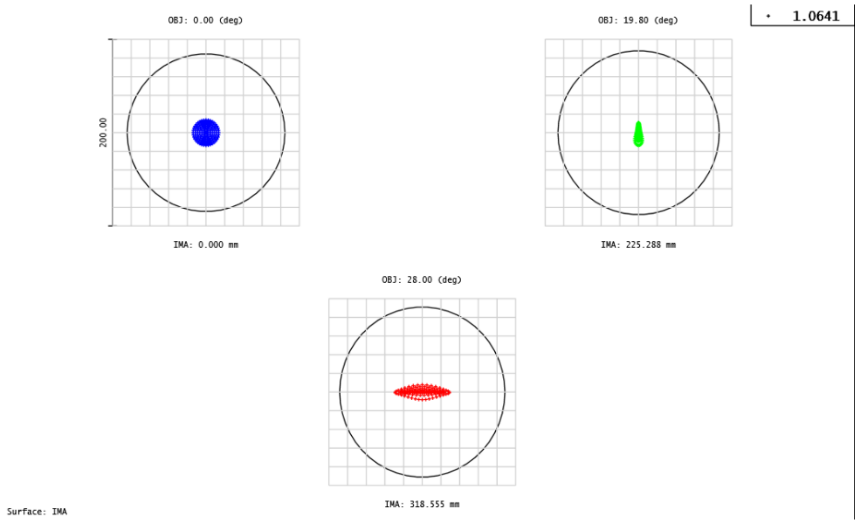

Fig. 4.2 Spot diagram

From the equation (3.1), the calculated radius of Airy disc is 84.38 µm, shown as the circle in the Fig. 4.2. The spots that are traced through the F-Theta lens are within the Airy disc, which means the performance of the designed F-Theta lens is within diffraction limited.

Fig. 4.3 shows the relative illumination curve of the laser beam across the workpiece surface after passing through the F-Theta lens. The abscissa represents the

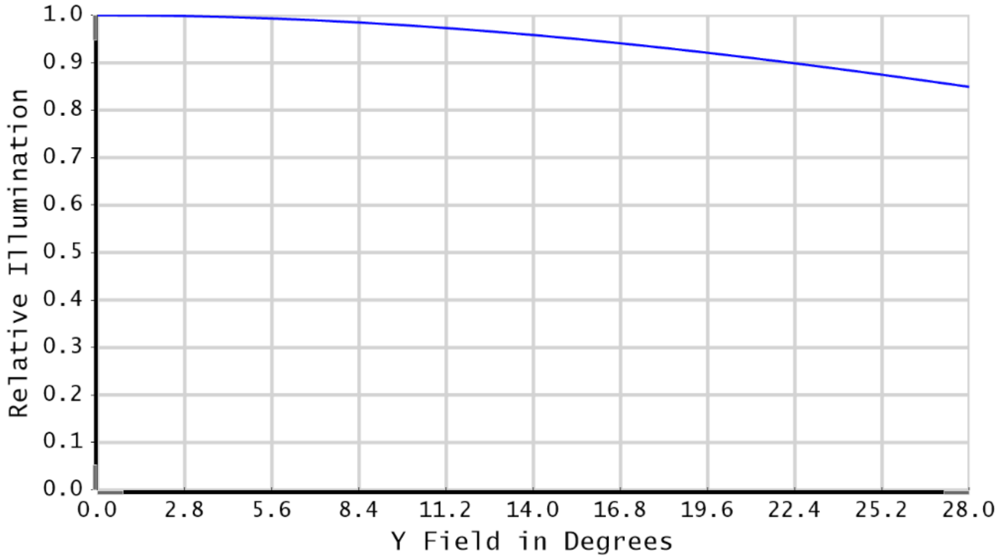

Fig. 4.3 Relative illumination

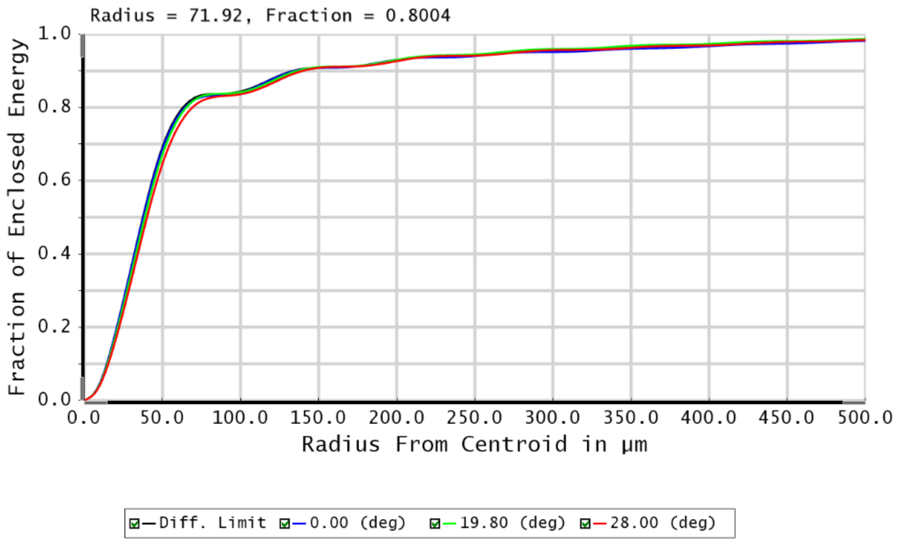

Fig. 4.4 Encircled energy

field of view (in degree), and the ordinate is the ratio of the illumination at the corresponding field of view to the central field of view. The relative illumination is close to 90% and is quite uniform in the whole working surface. It achieves the constant depth and thickness of the engraved line, which satisfies the practical requirements.

Fig. 4.4 shows the measure of concentration of energy in the image plane. 80 percent of the incident laser energy is focused within a circle of 72 μm in radius.

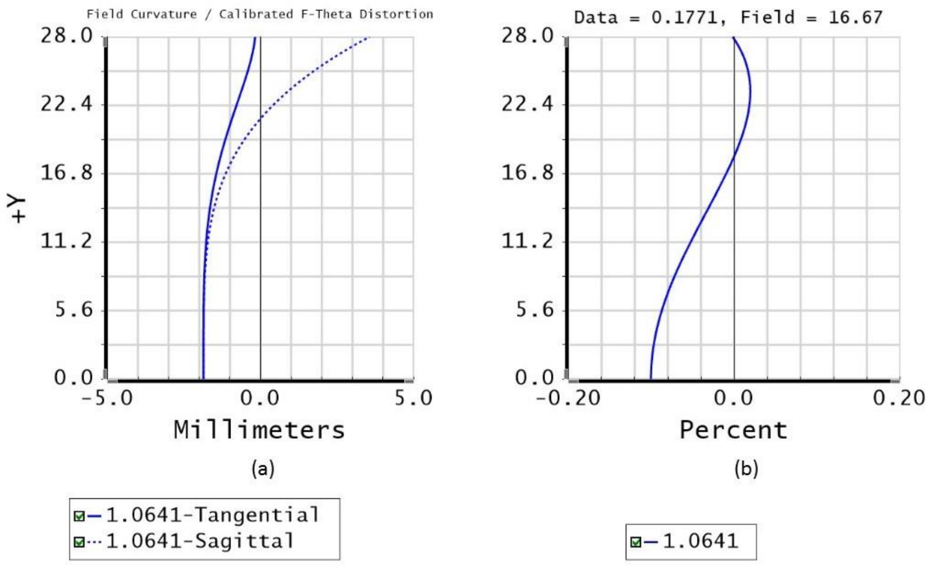

Fig. 4.5 Field Curvature / Calibrated F-Theta Distortion

Fig. 4.5 (a) shows the field curvature. The abscissa is the field curvature and the ordinate is the field of view. The solid curve is the tangential field curvature and the dashed curve is the sagittal value. The astigmatism is the difference between them at the same field of view. Although the optical system has the field curvature and the absolute value of the astigmatism is large, the flat field condition is considered in the calculation of the initial structure under the primary aberration theory. The final image plane is obtained by automatically optimization and aberration correction so that there are remnant field curvature and astigmatism to balance the other aberrations.

The maximal astigmatism shown in the figure is about 3.5 mm that is less than the focal depth. Therefore, the astigmatism of the designed F-Theta lens is permitted. Fig. 4.5 shows the calibrated F-Theta distortion across the field of view. It indicates the deviation from linearity of the F-Theta condition. The F-Theta linear relation is given by the equation (2.5). As long as the relative deviation is smaller than 0.5%, the lens system can be considered to meet the F-Theta linear relationship that can be used for the marking machine in practical use. Thus, the designed F-Theta lens satisfies the F-Theta linear relationship.

5 CONCLUSION

In this master's report, the F-Theta lens design is described in detail from the F-Theta lens theory, the initial structure, and the image quality evaluation. An F-Theta lens with large working area is presented.

The designed F-Theta lens is a compact optical system with the simple structure and large working area. Its working area is 640 mm in diameter. It consists of only four spherical lenses and the largest aperture among them is approximately 120 mm. Its tube length is less than 100 mm. Its field of view is $\pm 28°$ which corresponds to $\pm 14°$ deflection angle of the oscillating mirrors. Additionally, its focusing performance is within diffraction limited across the working surface. Its relative illumination is close to 90% and quit uniform, and its distortion, calibrated F-Theta distortion, is less than 0.1% that meets the F-Theta linear relationship well.

As the working area increases, there are higher requirements for aberration correction. At the same time, the lens element spacing and caliber will become larger, will make the lens becomes bulky, resulting in processing difficulty and cost. Therefore, aspheric surface may be considered in the system in the future, to improve its focusing performance with large working area and to keep its compactness.